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| 1. | Your reference | LB1524 |
| 2. | Patent application number *(The Patent Office will fill in this part)* | 0212739.7 |
| 3. | Full name, address and postcode of the or of each applicant *(underline all surnames)* | University of Sussex<br>Falmer<br>Brighton<br>BN1 9RH |
| | Patents ADP number *(if you know it)* | 625486003 |
| | If the applicant is a corporate body, give the country/state of its incorporation | United Kingdom |
| 4. | Title of the invention | Improvements in or relating to the Measurement of Two-Phase Fluid Flow |
| 5. | Name of your agent *(if you have one)* | Barker Brettell |
| | "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)* | 10-12 Priests Bridge<br>LONDON<br>SW15 5JE |
| | Patents ADP number *(if you know it)* | 7442494003 |
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| Request for preliminary examination *(Patents Form 9/77)* | 1 |
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11. I/We request the grant of a patent on the basis of this application.

Signature Barker Brettell Date

**Barker Brettell** 31 May 2002

12. Name and daytime telephone number of person to contact in the United Kingdom Lance Butler Tel: 020 8392 2234

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# IMPROVEMENTS IN OR RELATING TO THE MEASUREMENT OF TWO-PHASE FLUID FLOW

This invention concerns improvements in or relating to the measurement of two-phase fluid flow.

In particular the present invention has reference to the determination of the relative magnitude of each phase in a two-phase gas-in-liquid flow regime by analysis of the sensor signal from a conventional single-phase flowmeter.

There are many different types of flowmeter including the orifice plate/DP flowmeter, the turbine flowmeter, the Coriolis flowmeter, the electromagnetic flowmeter, and the vortex flowmeter, each employing different operational mechanisms and methods of detecting the flow being measured to yield a metered reading. The selection of the flowmeter type will depend *inter alia* upon the specific application, its cost, reliability and accuracy. Each type has its attendant disadvantages and advantages.

The present invention has particular, although not exclusive reference to vortex flowmeters in which *Von Karman* vortices are generated by the presence of a bluff body, for example a shedder bar, placed perpendicular to the direction of flow across and centrally within the confining conduit in which the fluid flows.

Consider in Figure 8 of the accompanying drawings a cylindrical bluff body diameter D immersed in a flowing fluid. If the Reynolds Number is less than 0.5, the two boundary layers around the cylinder do not detach because the pressure gradients (which depend on $v^2$) are very small. For Reynolds Numbers between 2 and 30 the flow boundary layers separate symmetrically producing two mirror image vortices before the flow

recombines. As the Reynolds Number is increased the vortices start to shed alternately from each side of the cylinder producing two staggered rows of vortices. This is the Karman Vortex Street. Each vortex is in the field of every other vortex so if such a system of vortices could exist in a stationary fluid the system would move upstream.

Under real conditions the frequency of vortex shedding is determined by the Strouhal Number, St, which for a cylindrical bluff body is $fD/U$ given by $fD/U = 0.198\ (1 - 19.7/Re)$. f is the vortex shedding frequency, D is the diameter of the cylinder, U is the mean flow velocity, and Re is the Reynolds number.

Hence $Q = k_1 \times f$

where Q is the volumetric flow rate

and $k_1$ is a constant

The frequency of the vortex shedding is only a function of the velocity of the flowing fluid and is essentially independent of its physical properties *inter alia* temperature, pressure, density, viscosity, conductivity, etc., provided that the presence of vortices can be sensed reliably and practically and this typically depends on the Reynolds Number being greater than about 10,000.

In the operation of the vortex flowmeter, the most widely used method of detecting the shedding of the vortices involves the sensing of a change in the fluid pressure at a fixed point adjacent to the vortex shedding body caused by the transit of the vortices using either a differential pressure sensor or by sensing the force exerted by the moving vortices on a fixed vane, or by sensing the torque exerted by the vortices on the vortex shedding body or by observing the effect of the vortices on a transverse ultrasonic beam.

A unique feature of the vortex flowmeter is that the effect of the vortex shedding body on the fluid flow is essentially the same as that caused by any obstruction or change in the cross section of the conduit in which the fluid is flowing and is in accordance with Bernoulli's equation:

$$P/\rho g + v^2/2g + z = \text{constant}$$

Hence the pressure drop across the vortex shedding body is a function of the square of the flow velocity as well as the density of the flowing fluid.

and $Q = k_2 \times (\Delta P/\rho)^{1/2}$

where Q is the volumetric flow rate

$\Delta P$ is the differential pressure developed across the vortex shedding body

$\rho$ is the density of the fluid

and $k_2$ is a further constant

In a steady flow rate regime and when a differential pressure sensor is used to detect the vortices, the sensor signal from the vortex flowmeter is characterised by variations in periodicity of as much as ± 10% and even wider fluctuations in amplitude. It is customary, therefore, to condition the sensor signal so that these fluctuations are eliminated. For a typical vortex flowmeter operating in a single-phase fluid, the frequency of the vortex shedding is proportional to the volumetric flow rate $Q$ and the average amplitude ($A_0$) of the vortex sensor signal increases as the square of the volumetric flow rate:

That is $A_0 = \alpha Q^2$

where $\alpha = \dfrac{\rho\gamma Gcp}{A}$

and $\rho$ = the fluid density (kg/m$^3$)

G = the gain of the amplifier

$\gamma$ = the sensor sensitivity ($VN^{-1}\ m^2$)

$A$ = the area of the pipe line ($m^2$)

$C_p$ = the pressure coefficient which is constant for the same line size of flowmeter

In order to determine the power and rms amplitude of the vortex sensor signal, the power is calculated by summing the sample signals *x(n)* according to the equation:

$$\text{Signal power} = \frac{\sum_{n=1}^{N} x^2(n)}{N}$$

where N is the number of sampled data points, and the rms signal amplitude can be calculated from the square root of the signal power.

In some industries, notably for example the oil industry, the flowing fluid may not be a single component. For example, it may be a hydrocarbon liquid in which there is entrained a significant proportion of hydrocarbon gas, or it may be the reverse where the principal component is a hydrocarbon gas which is carrying a significant proportion of hydrocarbon liquid in the form of droplets.

Alternatively, it may be a single component fluid which is flowing under conditions of pressure and temperature where it can exist as either a liquid or gas. In all these cases, it is a requirement to establish during operation of the relevant process or activity, not only the volumetric or mass flow rate but also the relative magnitudes of the individual phases. In other fields for example in steam generation, steam quality in terms of its wetness is an important characteristic influencing the overall efficiency of the relevant plant.

It is therefore an object of the present invention to provide a method of metering two-phase fluid flow to yield either the volumetric flow rate of each component of a two component fluid or the relative magnitudes of the phases in a single component two-phase flow.

According to the invention there is provided a method of metering fluid flow in a closed conduit including the disposition of a flowmeter through which the fluid to be metered flows, generating a signal indicative of at least one characteristic of the fluid flow, measuring the amplitude and frequency components and power of the signal and retaining the fluctuations associated therewith, and analysing the said signal features to determine the volumetric flow rate of at least one fraction of the fluid flow.

Conveniently the flowmeter is a vortex flowmeter in which the means of sensing the signal generated by the flowmeter may be of the differential pressure type. It is to be understood that the use of a flowmeter other than a vortex flowmeter is within the scope of the invention.

The method of the invention also includes the steps of calibrating the flowmeter by the use of reference flowmeters to accurately establish the flow rates of the components before they are mixed to form the two-phase flow to be measured by the flowmeter, in order to determine a relationship between signal power, signal amplitude (rms), the shedding frequency in relation to a vortex flowmeter, the signal fluctuations, and the flow rate. For two-phase flow measurement, the calibration of the flowmeter involves the conduct of a test programme to give performance data over a range of flow rates with single and two-phase flow. In particular two-phase flow was selected by the inventors in terms of providing one distinct primary phase and a distinct secondary phase; for example water was the primary phase with the secondary phase being air. Essentially therefore the calibration was carried out on the basis of gas-in-liquid phases, but it will

be appreciated that the calibration could be carried out with the phases in reverse.

The calibration yields graphical data on the measured signal features providing volumetric flow measurements enabling the use of the flowmeter to determine the presence of single or two-phase flow, and to measure the volumetric flow in single component flow, or the volumetric flows of both components in two-phase flow.

It has been found that the presence of a secondary phase within a primary phase occasions a change in the features of the flow measurement signal. Thus for example in the case of air being introduced into water flowing at a constant rate, this produces changes in the measured signal features. The vortex shedding frequency, which is an indicator as to the mean velocity of flow, increases with a decrease in the amplitude and power of the sensor signal, and it is this decrease which hitherto has been regarded as redundant that provides the important information regarding to the phase fractions in the two-phase flow.

The relative magnitude of the two phases in a gas-in-liquid flow regime can be determined by analysis and manipulation of the sensor signal from a vortex flowmeter in particular.

It is envisaged that the method of the present invention may be applied to flow regimes other than that indicated above, and accordingly could be applicable to liquid-in-liquid flow regimes where the liquids are immiscible, liquids or gases with entrained solids, and three-phase flow regimes.

By way of example only there follows a description of the utilisation of a vortex flowmeter to generate a signal indicative of the volumetric flow rate

of two components of two-phase gas-in-liquid fluid flows with reference to the accompanying figures in which:

Figure 1 depicts a typical signal power spectrum of the sensor signal from a vortex flowmeter;

Figure 2 shows the variation of the power spectrum with liquid flow rate for a vortex flowmeter with single-phase flow;

Figure 3 shows the change in the amplitude and frequency of the vortex sensor signal resulting from the introduction of a secondary phase (air);

Figure 4 shows a change in the vortex shedding frequency with flow rate of the primary phase (water) resulting from the introduction of a secondary phase (air);

Figure 5 represents a change in the amplitude of the vortex sensor signal with flow rate of the primary phase (water) and the introduction of a secondary phase (air);

Figure 6 shows a change in the rms amplitude of the vortex sensor signal with the primary phase (water) flow rate for different flow rates of a secondary phase (air);

Figure 7 represents the output from a neural network; and

Figure 8 is a diagram representing a bluff body and illustrating vortices generated during fluid flow.

As has hereinbefore been explained vortex flowmeters depend for their operation on the alternate shedding of vortices from the two edges of a bluff body positioned perpendicular to the direction of flow in the stream of fluid. The frequency of the vortex shedding is proportional to the velocity of flow and the frequency spectrum of the sensor signal from a typical vortex flowmeter is shown in Figure 1.

When the flowmeter is operating on a single-phase liquid, the amplitude of the signal increases according to the square of the vortex shedding

frequency, as shown in Figure 2. This relationship is a direct function of the pressure drop developed across the vortex shedding bar and confirms that Bernoulli's equation (shown *supra*) applies to the operation of the flowmeter.

If the flow of the primary phase (water) is held constant, the introduction of a secondary phase (air for example) causes the shedding frequency to rise, because of the increased total volume of the flowing fluid. However it also causes the amplitude of the vortex sensor signal to fall, as shown in Figure 3, but much more rapidly with increasing air fraction than could be explained if the mean density of the two-phase mixture is inserted for the density $\rho$ in the Bernoulli equation.

If the flow rate of the primary phase (water) is held constant at a particular flow rate, the introduction of a secondary phase (air) causes the frequency of the vortex shedding to rise. This result is shown in Figure 4 for a series of five fixed primary phase flow rates.

When operating on a single-phase flow, the relative amplitude of the sensor signal is directly proportional to the square of the shedding frequency, as show in Figure 5. If a secondary phase (air) is introduced, the relative amplitude of the signal falls away progressively. It is therefore possible to plot a series of curves which correlate the vortex shedding frequency with the volumetric flow rate and hence the relative magnitude of the two phases.

The power and the amplitude of the vortex sensor signal over a range of two-phase flows are shown in Figures 5 and 6 respectively. Each curve shows the signal as the primary phase (water) flow rate is varied for a fixed secondary phase (air) flow rate.

To determine the relative magnitudes of the individual flows in a two-phase regime, the flowmeter must first be calibrated involving the measurement and plotting of the amplitude and shedding frequency of the sensor signal

over the range of single-phase flows of the primary fluid to be covered by the flowmeter. The procedure must then be repeated with the flow rate of the primary fluid held constant, but with the flow rate of the secondary fluid varied throughout the range to be covered. Figures 4, 5 and 6 are examples of such calibrations.

In this context Figures 4, 5 and 6 show the results of measurements made at pressures up to 3 bar on a (1½ inch) Foxboro Model 83F Vortex Flowmeter. For Figure 4 the frequency of vortex shedding was measured with the flow rate of the primary phase (water) held constant at five different values and while the flow rate of the secondary phase (air) was adjusted from zero to the maximum in five equal steps. For Figure 5 the signal power and vortex shedding frequency were measured with the flow rate of the primary phase held constant at five different values and the flow rate of the secondary phase was adjusted from zero to the maximum in five equal steps. For Figure 6 the signal amplitude and vortex shedding frequency were measured with the flow rate of the primary phase held constant at five different values and the flow rate of the secondary phase was adjusted from zero to the maximum in five equal steps. On the basis of these plots the flow rates of the two phases can be determined for any set of conditions within the calibrated range. Thus if the vortex shedding frequency is for example 100 Hz and the signal amplitude is about 0.64 V, then the data in Figure 6 show that the flow rate of the primary fluid is about 260 l/min and that of the secondary phase is about 10 l/min.

It is evident that a series of curves which correlate the vortex shedding frequency with the mass flow rate can be prepared for other line sizes of vortex flowmeters and from them the relative magnitude of the two-phases can be deduced.

It is clear that the magnitude and the power of vortex sensor signal discriminate between the measurement signals when different amounts of secondary phase are introduced into the primary phase. Figures 5 and 6 show the systematic but non-linear relationships exhibited between the observable quantities (shedding frequency, amplitude and power of vortex sensor signal) and the flow rates of individual phases, namely the primary phase (water) flow rate and the secondary phase (air) flow rate, which the flowmeter should ideally measure. A multi-layer neural network is capable of fitting complex non-linear data, and therefore provides a method for handling the observable data to produce a system which can yield good measured values for both the primary and the secondary phase flow rates.

Four input data values from the vortex flowmeter are used as inputs to the neural network and they are the shedding frequency, signal power, rms signal amplitude, and the square root of rms signal amplitude. The network is trained to generate two output values, the primary phase (water) flow rate and the secondary phase (air) flow rate from the four input values.

Two separate sets of vortex sensor signal are collected with the same conditions. The outputs of the neural network after training and testing are shown in Figure 7 and the detailed data are given in Table 1.

The present invention thus provides a method for characterising a fluid flow by using the noise of the sensor signal as an indication as to the status of that flow, namely whether a single or two-phase flow is present. The invention represents a clear departure from the conventional approach in flow measurement which seeks to discard the fluctuations in the signal whereas the present applicants have understood the importance attaching to the information transmitted by the noise.

CLAIMS

1. A method of metering fluid flow in a closed conduit including the disposition of a flowmeter through which the fluid to be metered flows, generating a signal indicative of at least one characteristic of the fluid flow, measuring the amplitude and frequency components and power of the signal and retaining the fluctuations associated therewith, and analysing the said signal features to determine the volumetric flow rate of at least one fraction of the fluid flow.

2. A method according to Claim 1 in which the flowmeter is a vortex flowmeter.

3. A method according to Claim 1 or 2 in which the means of sensing the signal generated by the flowmeter is of the differential pressure type.

4. A method according to Claim 2 or 3 as dependent on Claim 2 and including the steps of calibrating the flowmeter using a reference flowmeter thereby to determine a relationship between signal power, signal amplitude, the shedding frequency of the vortices generated within the vortex flowmeter, the (rms) signal amplitude, and the flow rate.

5. A method according to Claim 4 in which the calibration includes conducting a series of tests to provide performance data over a range of flow rates with single and two–phase flows.

6. A method according to Claim 5 in which the calibration is conducted with two-phase flow on the basis of gas-in-liquid phases.

7. A method according to Claim 5 in which the calibration is conducted with two-phase flow on the basis of liquid-in-gas phases.

8. A method according to any one of the preceding claims in which the measurement data generated by the calibration is used to provide a volumetric flow measurement matrix.

9. A method according to Claim 8 in which the volumetric flow matrix is employed to determine the presence of single or two-phase flow.

10. A method according to Claim 9 in which water is flowing at a constant rate and air is introduced thereby causing an increase in the mean velocity of flow, the increase in the mean velocity of flow being itself indicative of the presence of a secondary.

11. A method according to Claim 10 in which an increase in the vortex shedding frequency occasioned by virtue of an increase in the mean velocity of flow is accompanied by a decrease in the amplitude of the sensor signal.

12. A method according to Claim 11 in which the decrease in amplitude is used as a determinant as to the presence of a secondary phase.

13. A method according to Claim 11 in which the relative magnitude of the two phases is determined by the analysis and manipulation of the sensor signal from the vortex flowmeter.

14. A method of metering fluid flow substantially as hereinbefore described with reference to the accompanying figures.

## ABSTRACT OF THE INVENTION

### IMPROVEMENTS IN OR RELATING TO THE MEASUREMENT OF TWO-PHASE FLUID FLOW

In a method of measuring two-phase fluid flow a vortex flowmeter is used to generate a signal indicative of the flow regime using fluctuations in the signal to determine the phase status of the flow.

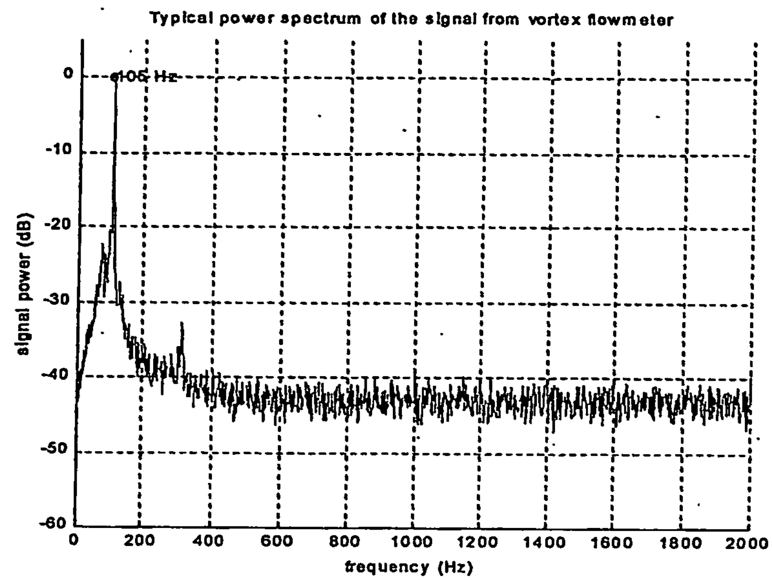


Figure 1 Typical power spectrum of the sensor signal from a vortex flowmeter

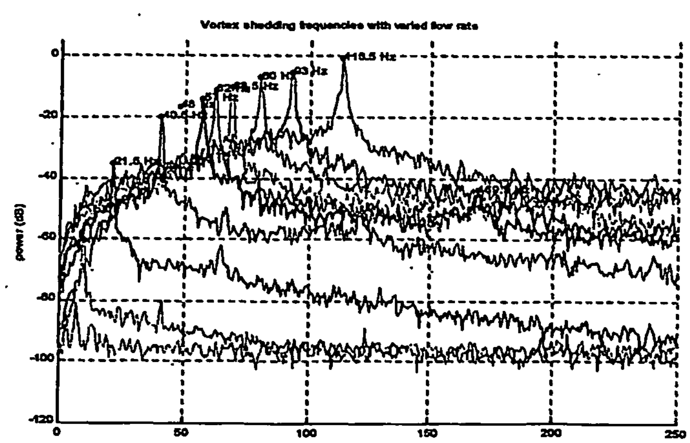


Figure 2 Variation with liquid flow rate of the power spectrum of a vortex flowmeter

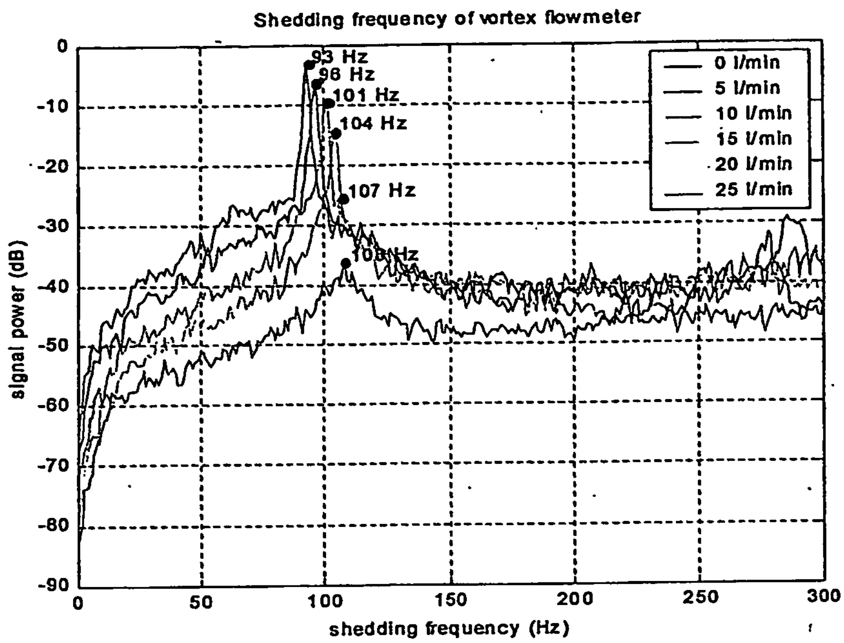


Figure 3 Change in the amplitude and frequency of the vortex sensor signal resulting from the introduction a second fluid phase

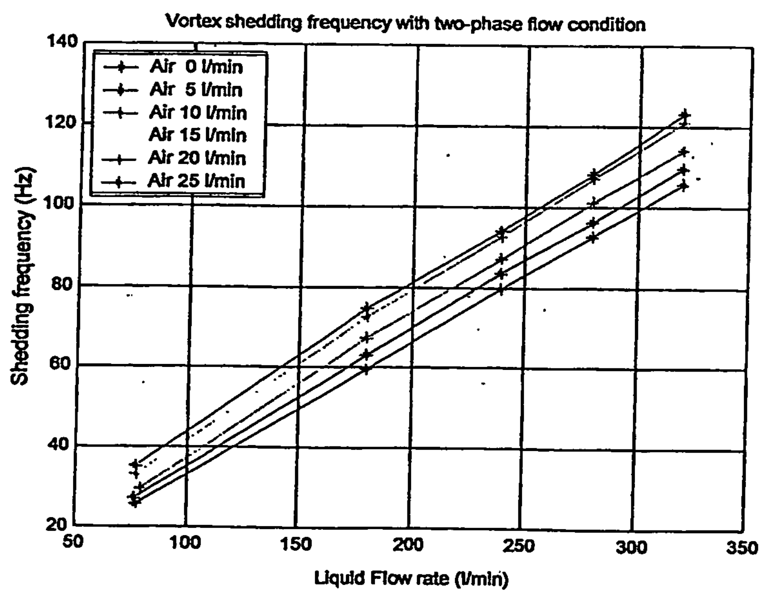


Figure 4 Change in vortex shedding frequency with flow rate of the primary phase (water) resulting from the introduction of the second phase (air)

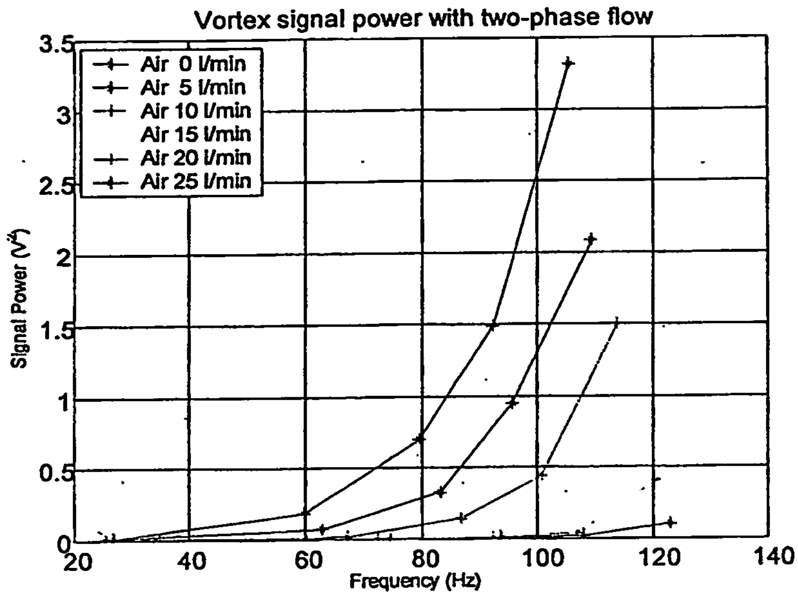


Figure 5 Change in power of the vortex sensor signal with flow rate of the primary phase (water) and the introduction of a second phase (air)

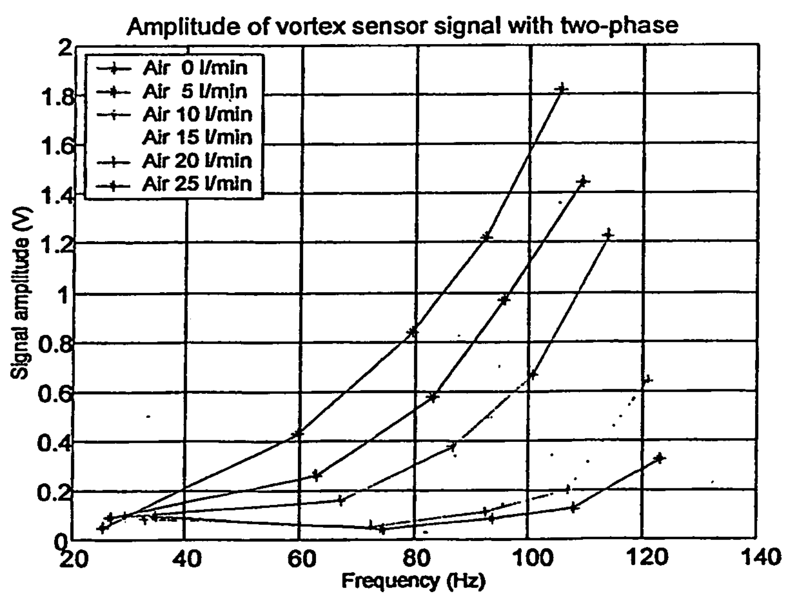


Figure 6 Change in the rms amplitude of the vortex sensor signal with the primary phase (water) flow rate for different flow rates of a second phase (air)

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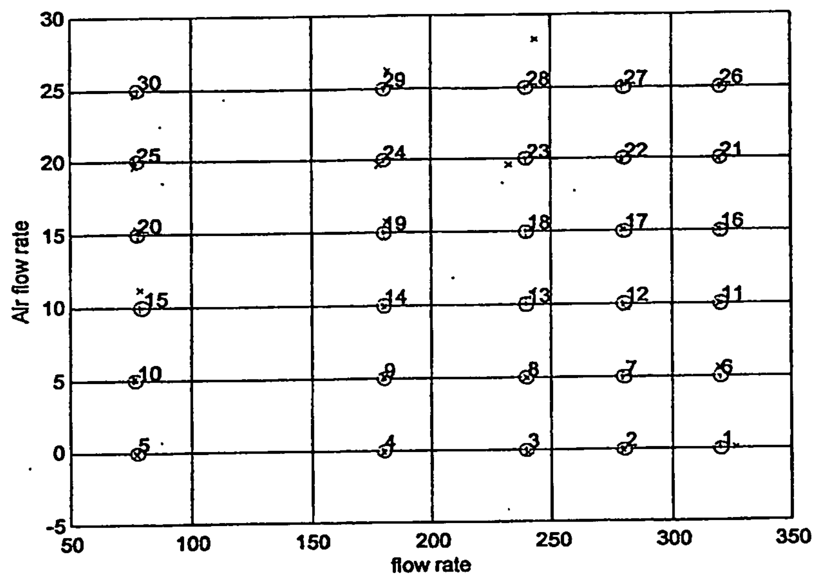


Figure 7. The output from neural network

o --- training targets * --- Neural outputs after training
x --- tested outputs of the network

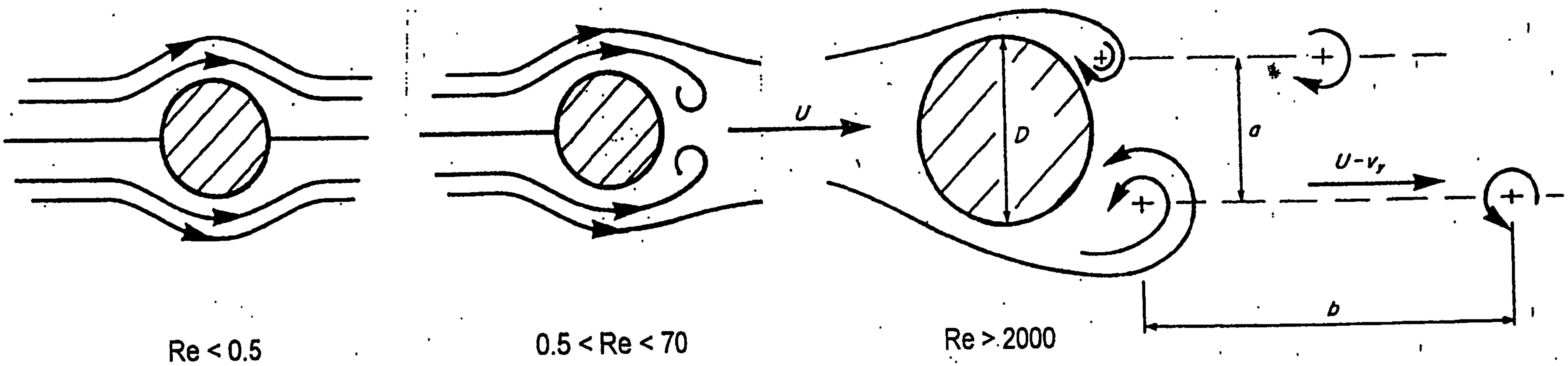


FIGURE 8